Blackbird UAS Project Description

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Submitted:
May 28, 2008

Proof of Flight Statement: We certify that the Unmanned Aerial Vehicle described in this paper has undergone approximately six hours of fully autonomous test flight.

Abstract

The Blackbird Unmanned Aerial System (UAS) has been developed using a systems design approach. The system is defined to include the air vehicle, payload, flight controller, ground station, communications equipment, software and human operators. Design decisions were made based on total system design and the effect on overall mission performance, especially the key performance parameters (KPP). Subsystems ranging from the custom-designed airframe and electric drive motor to the packaging of the ground station were all based on this system-design philosophy. The team recognized from the outset that the interaction of human operators with the system and with each other during the mission would be critically important to overall mission success. At each step of the design process, the team attempted to justify decisions through analysis of the expected performance of both the individual subsystems and the overall system. For example, we recognized that high-resolution images were most valuable to ground operators when results could be interpreted in real time. We also attempted to validate our decisions through experimental evaluations of system performance.

1 Introduction

The Autonomous Vehicle Team of Embry-Riddle Aeronautical University is proud to introduce Blackbird, a new vehicle platform designed to compete in the 2008 AUVSI UAS Competition. Blackbird incorporates many of the successful features and subcomponents used by other competitors in recent years, but the design also includes several key innovations specifically developed for the 2008 competition. Our goal is to make use of the knowledge and experience gained by previous teams while attempting to address the most critical problems and provide the best overall value. The name Blackbird was chosen in honor of the famous strategic reconnaissance aircraft, the Lockheed SR-71 Blackbird. We hope to live up to the lofty expectations our vehicle name and heritage may suggest.

2 Innovations

The Blackbird UAS presents three key innovations:

- Superb aircraft durability and maintainability with the carbon-fiber *Vampire 9S* airframe.
- Professional grade target imagery with the *Target Stalker* and *RAPTOR* systems.
- Powerful onboard computing with the *Mac Aero*.

In 2007, the team made many key improvements to the system: Use of an electric motor to reduce vibration, a folding prop for increased efficiency, hand launching with a belly landing for operation on unimproved surfaces, and a durable airframe. For 2008, the team wished to improve the system in five areas: Safety, repeatability, performance, survivability, and simplicity. An overview of these innovations will be given below, with more detailed explanations following in section four.

2.1 Innovation #1: Vampire 9S

The Vampire 9S is a custom airframe with a total wingspan of 9 feet and an overall length of 6.1 feet. It has an empty weight of 20 pounds and a fully loaded weight of 30.6 pounds. Vampire has no landing gear, instead using catapult launching and a deep-stall belly landing, which allows for operation in a wider variety of flying sites.

Construction is almost entirely carbon-fiber, providing durability. Vampire uses a pusher configuration with the motor, a 2.2 kW Hacker A60-18M brushless outrunner powered by 12 lithium polymer cells, in the rear of the aircraft, decreasing the aircraft surface area affected by prop wash and allowing a forward-looking camera to be placed in the nose. The aircraft uses only two control surfaces, both of which are located in its inverted v-tail. The omission of control surfaces in the wing increases efficiency of the airfoil and simplifies wing construction and repair.

2.2 Innovation #2: Target Stalker and RAPTOR

Blackbird is capable of taking professional grade high resolution pictures of targets using a system the team has named *Target Stalker*. The system uses a Canon 400D digital single lens reflex (DSLR) camera with a 10.1 megapixel complementary metal-oxide-semiconductor (CMOS) sensor. As the operators take pictures of potential targets, each photo is automatically embedded with highly precise data on Blackbird's position provided by a NovAtel 20 Hz update rate, 2 cm positional accuracy differential GPS [1].

Complimenting the Target Stalker is another innovative system called RAPTOR (rapid asynchronous photo transfer and retention) system, which handles the technical aspects of shooting, transferring, and storing photos taken by Blackbird. The data-link has sufficient bandwidth to transfer the full resolution images at a rate of 0.2 Hz, but RAPTOR allows the operator to take pictures at a rate of 1.5 Hz in burst fire mode for four consecutive images, or at 1 Hz in continuous mode while the images transfer asynchronously in the background. This is useful, as asynchronous shooting and transfer allows the operator to capture and embed target images as necessary. Images are transferred using the available bandwidth at all times during flight, not only while the aircraft is over the target area. A lower resolution Firewire video system using a Point Grey Research Firefly operating in real time at a frequency of 60 Hz allows the operator to select prime areas for targeting.

2.3 Innovation #3: Mac Aero

Interfacing with the Canon 400D is the onboard computer, a modified Apple Macintosh Mini dubbed *Mac Aero*. The Mac Mini is a powerful computer in a small form factor (6.5" x 6.5" x 2"). In constructing the Mac Aero, many of the Mini's components had to be ruggedized. The stock hard drive was replaced with an durable 8GB solid state drive, capable of withstanding shocks during operation of up to 1500G [2]. The external AC to DC power supply was replaced with an internal DC to DC regulator, allowing the Mini to run from batteries, and the DVD burner was completely removed to reduce power draw. The stock WiFi patch antenna was replaced with a 1 Watt amplifier and 5.5dBi omnidirectional antenna [3].

3 Development Process

3.1 Approach

The team adopted a systems engineering process that takes elements from the Siemens 4-view Architecture Model [4], the Software Engineering Institute's Quality Attribute Workshop [5], as well as Alistair Cockburn's Crystal Clear methodology [6].

The first step in the design of the system was to identify quality goals. Quality goals are broad statements that describe qualities that the final system should exhibit and are used to guide the development process. Next, the team defined a set of "issues" that were created in a tabular format. Issue tables are meant to outline a particular design issue such as "durability of the airframe" that will impact the architecture, and, by extension, the quality goals. Each issue table includes the title of the issue, a description, and the factors that influence the issue such as "ability of airframe to withstand shocks", and suggested strategies to address the issue. Each factor may include a series of questions to help guide the designers. Next, several candidate solutions were proposed and evaluated based on compliance with the quality goals. Finally, an architecture was created for the system and was further evaluated with reference to the quality goals of the system.

3.2 Quality Goals

An analysis of the rules and of past experiences were used to define a set of desired quality goals for the UAS. When designing the system, all goals must be taken into account. Increasing the system's ability to meet one goal will often incur a tradeoff with respect to another goal; competing goals must be balanced when considering solutions.

Quality Goal 1: Safety

Safety is the first requirement to be considered in the design of the system. Safety considerations should take precedence over other quality goals in the design of the UAS.

Quality Goal 2: Reliability/Repeatability

The system must be capable of operating reliably and producing repeatable and predictable results.

Quality Goal 3: Efficiency/Performance

The system must be capable of efficiently and effectively carrying out its mission. All subsystems of the UAS must be able to meet or exceed performance requirements necessary to carry out the mission. The mission's *Key Performance Parameters* (KPP) are encapsulated within this quality goal. The KPPs are as follows: Autonomy worth up to 30%, imagery up to 20%, target location up to 20%, mission time up to 10%, in-flight re-tasking 5%.

Quality Goal 4: Survivability/Maintainability

In the design of the system, the team must take steps to ensure the system is easily maintained and provides good survivability for all components under the stresses of everyday operations. Minimizing the downtime and expenses associated with component failure and replacement or repair is a critical objective. Incidents such as hard landings can be expected, and these must not interfere with the preparation for mission and competition.

Quality Goal 5: Simplicity

The system should be as simple as possible while still being capable of carrying out the mission. By setting a goal for simplicity, the resulting UAS will be easier to use and maintain. Based on past experience this will benefit the everyday use of the system.

3.3 Issue Tables

This section describes the aforementioned issue tables that helped to outline the factors influencing the design and the strategies that might be used to address these issues. Each issue table is labeled with a unique identifier as are each of its factors and strategies. These identifiers are used in producing a system traceability matrix that can be useful in tracing features back to design decisions and quality goals. Each influencing factor is formatted with a statement of the influence that may be followed by a series of questions that are intended to guide the design. The strategies are statements of possible strategies to solving the issues. The strategy statements in the tables below are the result of extensive research, experimentation, and in some cases simulation. The team identified three specific issues believed to provide the greatest improvement on the overall success of the project:

- Issue Table 1: Ability to identify targets
- Issue Table 2: Durability of the system
- Issue Table 3: Bandwidth, range, and reliability of data-link

The completed issue tables are listed in tables 3.3.1 through 3.3.3.

Table 3.3.1: *Issue Table 1: Ability to identify targets*

***Issue Table* 1: Ability to identify targets**	
Description: The capability of identifying targets accurately and efficiently is critical to the success of the UAS.	
Influencing Factors	
IF1	Speed at which an operator can use the system to identify and collect attributes of a target. How many seconds does it take between the UAS flying over a target and that target being identified by the operator?
IF2	Color accuracy of the imagery. Are the colors washed out? Are the colors bleeding?
IF3	Resolution of the target in the imagery. How many pixels in image per inch of target? What is the resolution of the target in pixels?
IF4	Altitude and airspeed of the vehicle. How many seconds is a target in field of view? How long does it take to traverse the target area while obtaining total coverage of the area with the imaging system?
IF5	Accuracy of object targeting. What is the positional accuracy of targeting? What is the error between the location of the target given by the UAS and the actual location of the target?
Strategies	
ST1	**Description:** Use two (or more) operators, one to capture targets, one to identify them. **Benefits:** Potentially faster target acquisition, asynchronous, scales well. **Drawbacks:** Need more operators, could cause communication problems.
ST2	**Description:** Use an RTK GPS. **Benefits:** Greater positional accuracy (within 2cm with RTK correction). **Drawbacks:** High cost, around $16k for complete system. **Possible Solutions:** Novatel RTK GPS

Issue Table 1: Ability to identify targets	
ST3	**Description:** Use a low-res (480 lines) camera. **Benefits:** Simple and inexpensive. **Drawbacks:** Low target resolution. Calculated target resolution of 7.04pix*. **Possible Solutions:** KX141 analog video camera with video radio transmitter and receiver. Digital USB, Firewire or internet protocol camera with digital transmission such as WiFi (802.11x).
ST4	**Description:** Use a hi-res video camera (720+ lines). **Benefits:** Higher resolution of targets. With a 1080 line video camera, the resolution of a target is 47.5pix*. **Drawbacks:** Expensive. Bandwidth required to transmit video back to the ground in the range of 15-500 MBits/sec. Many high resolution industrial video cameras use a rolling shutter, which produces an undesirable video distortion when placed in a moving vehicle. **Possible Solutions:** Avigilon 2.0MP-HD-C, Arecont Vision AV2100
ST5	**Description:** Use a hi-res still camera (6 megapixels +). **Benefits:** Mechanically simple, wide selection of off-the-shelf cameras and lenses, high resolution (at 3000 lines per image, target resolution is 230.8pix*). **Drawbacks:** Frame rate limited by the camera used and downlink bandwidth. Added complexity in interfacing with the camera. **Possible Solutions:** Digital point-and-shoot (Canon S6, Nikon P3), digital single lens reflex (Canon 40D, Nikon D300), digital HD firewire camera (Point Grey Grasshopper)
ST6	**Description:** Use wide-angle lenses (greater than 90 degrees field of view). **Benefits:** Operator can see more of the target area at a given altitude in a fixed time frame than with a larger field of view lens. With a 10.1MPix camera and a 110 degree diagonal field of view (DFOV) lens has a viewing area of 0.0425 sq. mi. while the same camera can only see 0.025 sq. mi. with a 90 DFOV lens. **Drawbacks:** The resolution of the camera is fixed, so a larger field of view will reduce target resolution. Comparing a 90 DFOV lens to a 110 DFOV lens, target resolution drops from 230.8 pix to 135.9 pix.
ST7	**Description:** Use high-quality lenses. **Benefits:** Reduces image artifacts such as chromatic aberrations and blurring. Using a lens with a larger aperture allows the camera to expose the sensor over a shorter period of time, rendering sharper images. High optical quality lenses reduce chromatic aberrations (light is out of alignment, showing overlapping primary color ghost images of an object) so that fine details are clearer and are not blurred. **Drawbacks:** Expensive. If using a digital single lens reflex (DSLR), lenses can weight upwards of one pound.

Issue Table 1: Ability to identify targets	
ST8	**Description:** Use a gimbaled camera. **Benefits:** Ability to direct the movement of the camera to track targets and/or survey the target area independently of the movement of the aircraft. **Drawbacks:** Added mechanical complexity. Increased chance of critical failure -- if the camera becomes stuck in an undesirable position, it may become difficult to carry out the mission. Off the shelf solutions such as the Cloud Cap Technology TASE are expensive.
ST9	**Description:** Used a fixed-position camera. **Benefits:** Mechanically simple. **Drawbacks:** With the camera being fixed in place, the view of the camera is directly tied to the attitude and position of the aircraft.
* Target resolution and viewing area numbers are calculated for a 4'x4' target sighted at an altitude of 700ft AGL. Resolution is defined as pixel width multiplied by pixel height. Viewing area is defined in square statute miles.	

Table 3.3.2: *Issue Table 2: Durability of the System*

Issue Table 2: Durability of the system	
Description The durability of the airframe does not often effect the performance of the aircraft in its mission, however it does greatly improve the ability of the team to operate the vehicle before the competition. Over time, parts wear out, and in the event of an incident, repairs may be necessary. Minimizing the time and money lost to such events is important in the time before the competition.	
Influencing Factors	
IF6	Ability of the airframe to withstand shocks on landing and transport from the lab to the field. In the event of a very hard landing, what is the cost of repair and time until the aircraft is once again airworthy?
IF7	Ability of the avionics to withstand forces exerted upon them during takeoff, flight and landing maneuvers. Do the electronics shift in the airframe during maneuvers? In the event of landing gear failure, are there any exposed systems that would need to be repaired?
Strategies	

Issue Table 2: Durability of the system	
ST10	**Description:** Use a balsa wood aircraft. **Benefits:** Inexpensive, lightweight. **Drawbacks:** Balsa is fragile and plastic sheet coverings are easily torn and punctured during transport. Balsa aircraft can take more time to repair than a composite aircraft. **Possible Solutions:** Sig Rascal, Sig Kadet, Senior Telemaster
ST11	**Description:** Use a strengthened balsa wood aircraft, ie: using plywood sheeting in critical areas of the airframe. **Benefits:** More durable than a normal balsa wood airframe. **Drawbacks:** One of the benefits of using balsa, the low weight, is partially negated.
ST12	**Description:** Use a composite aircraft. **Benefits:** Durable and easy to repair. **Drawbacks:** Expensive. Not as readily available as balsa aircraft. Heavier than balsa. **Possible Solutions:** Scale gliders built from composite materials can be purchased as almost-ready-to-fly kits.
ST13	**Description:** Use shock absorbers for components and durable interconnects capable of interlocking. **Benefits:** Partially isolates electronics from vibration and reduces chances of interconnect failure. **Drawbacks:** Vibration dampers take up extra space and can be difficult to mount correctly. Locking interconnects can take up more space than stock interconnects and are more expensive.
ST14	**Description:** Provide strain relief for wiring. **Benefits:** Ensures that any wires pulled harshly by an operator or by shifting components are unlikely to fail. **Drawbacks:** Providing strain relief may require extra space in the component casing or inside the fuselage. Extra weight may be added. **Possible Solutions:** Use heat-shrink tubing , zip ties, and service loops.

Table 3.3.3: *Issue Table 3: Bandwidth and reliability of data-link*

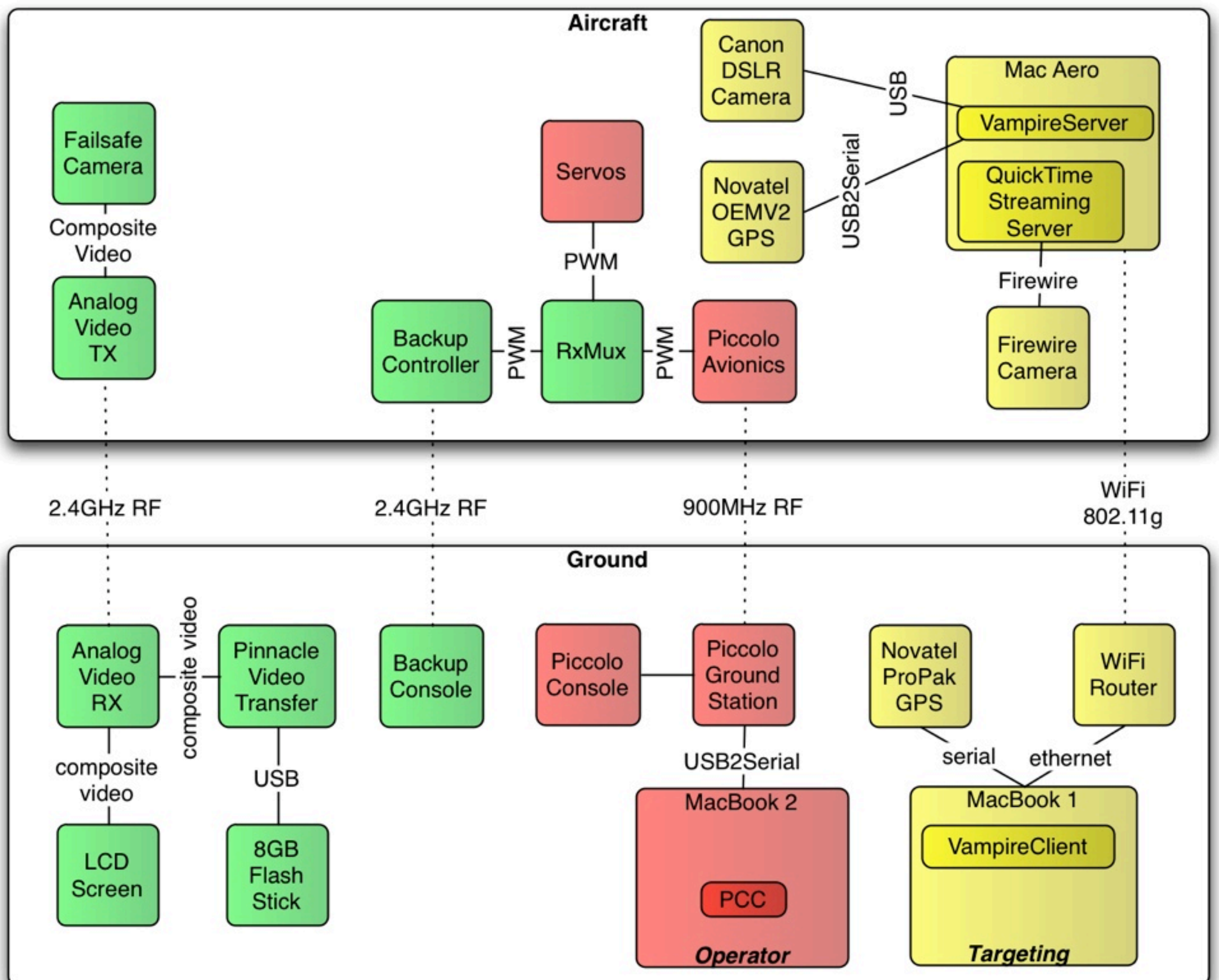
***Issue Table* 3: Bandwidth and reliability of data-link**	
Description The available bandwidth and overall reliability of the data-link directly affects the performance of the imaging system since it is geared towards an active intelligence mission for the UAS competition. These two features of the data-link are dependent on the type of transmitter/receiver and the antennas used to broadcast the signal.	
Influencing Factors	
IF8	Ability of the data-link to sustain the bandwidth needed for actionable intelligence gathering. How much bandwidth is required to obtain high-definition images in a reasonably short period of time?
IF9	Ability of the data-link to maintain performance at the maximum competition distances. What is the maximum distance the data-link can operate with a minimum loss of packets?
Strategies	
ST15	**Description:** Use a 802.11x TCP/IP network adapter. **Benefits:** High bandwidth. Theoretical maximum bandwidth of 11MBits/sec on 802.11b, 54MBits/sec on 802.11a/g, and 300MBits/sec on 802.11n. Wide variety of off-the-shelf devices. **Drawbacks:** Most off-the-shelf 802.11x network adapters have a shorter range when compared to radio modem solutions. Mostly made for consumer applications such as home and corporate networks. **Possible Solutions:** Integrated wireless network adapter in a computer, add-on cards, USB adapters, and standalone wireless access points.
ST16	**Description:** Use serial radio modems. **Benefits:** Long range. Available in OEM (original equipment manufacturer) packages, making integration with custom avionics easier. **Drawbacks:** Bandwidth generally <1MBit/sec. **Possible Solutions:** MaxStream, MicroHard, Aerocomm
ST17	**Description:** Use point-to-point microwave. **Benefits:** Long range and high bandwidth. **Drawbacks:** Expensive. Transmitters are heavy and large.

4 Design

4.1 Architecture

Design decisions such as which camera to use, the aircraft payload capacity, the autopilot, and presence of an onboard computer all act as architectural drivers. These architectural drivers shape the architecture of the system, dictating interface protocols, data flow between components, and the order in which components must be implemented. The architecture is divided into three major subsystems (*Figure 4.1.1*): Safety (left, in green), Autopilot (center, in red), and Target Stalker (right, in yellow).

Figure 4.1.1: Blackbird System Architecture



4.2 Autopilot

The autopilot system used for Blackbird is the Piccolo Plus from Cloud Cap Technologies. The Piccolo has the ability to fly waypoint-to-waypoint, can determine its orientation on all three dimensional axes., and contains a 900MHz Microhard radio modem that communicates directly to the ground station. All autopilot related data, such as telemetry and command and control are channeled through this long range link. The proven reliability of this link helps satisfy *Quality Goal 1: Safety*.

The Piccolo has robust waypoint navigation functionality, which satisfies *Quality Goal 3: Performance.* The autopilot also offers a mode of navigation called “pre-turn” where the aircraft will not attempt to hit a waypoint directly, but instead will begin turning toward the flight path leading away from the waypoint as it approaches its destination. This is useful in the tightly constrained airspace at the competition where waypoints may may be situated within 200ft of a no-fly boundary [7] as flying through the waypoint, depending on the angle of approach, could cause the aircraft to come dangerously close to the boundary.

The Piccolo can also be programmed with mission limits, which are important features to meet the team’s safety goals. Based on the mission requirements, specifically requirement 2.b.8 listed in the 2008 rules, if the communications are lost for more than 30 seconds, the Piccolo will close the throttle and apply full up elevator, right rudder, right/left aileron, and flaps. This should immediately put the aircraft into a spin to the ground, which ensures that the aircraft does not drift too far from its last known location, and will meet 2008 rules requirement 2.b.8.f.

The autopilot is the only device in the aircraft that is not provided with regulated voltage. This choice was made to allow the operator to monitor the battery voltage. Using a regulator to supply the Piccolo would have given the operator no warning if the batteries were low, as the regulated voltage would be the same until it simply dropped off to nothing. Using a voltage regulation device external to the Piccolo in combination with a separate power supply would have increased the complexity of the system, violating *Quality Goal 5: Simplicity* while also increasing the points of failure, offsetting any gains in *Quality Goal 1: Safety.*

4.3 Airframe

4.3.1 Evaluation of Airframes

The team had several criteria for aircraft selection based on quality goals and the mission’s key performance parameters.

Table 4.3.1: Airframe Evaluation Criteria

ID	Criteria
AEC1	Composite airframe which is listed in *Issue Table 2: ST12*
AEC2	Easily transportable which helps meet *Quality Goal 2: Repeatability/Reliability*
AEC3	Payload capacity of at least 7lb (calculated using estimated weight of components) which helps meet *Quality Goal 3: Efficiency/Performance*
AEC4	Takeoff and land from unimproved surfaces which helps meet *Quality Goal 2: Repeatability/Reliability*
AEC5	Capable of using an electric motor which helps meet all of the quality goals.
AEC6	Capable of accommodating a forward looking nose camera for *Quality Goal 1: Safety*

ID	Criteria
AEC7	Capable of cruising at 44.4mph fully loaded (determined using the spreadsheet in *Table X* to provide the operator with 10 seconds to identify a target on screen when using a 90 degree field-of-view lens), which helps meet *Quality Goal 3: Efficiency/ Performance*

Balsa airframes such as the Hobby-Lobby Senior Telemaster, Sig Manufacturing Rascal and Kadet were eliminated as they did not meet the composite airframe/durability requirement, AEC1. Many 13ft or greater wingspan scale model gliders met AEC1, AEC2, AEC3, AEC4, and AEC7, while failing to meet AEC5 and AEC6. One aircraft available from ICARE Sailplanes and Electrics in Canada, the Windex 1200x 4.1m, met all of the requirements, although it was expensive and it was unknown if the construction of the wings would be strong enough to handle the payload during standard mission maneuvers.

Figure 4.3.1: Windex 1200c

4.3.2 Vampire 9

As the team was deliberating on acquiring a Windex for testing, a local company, DynaWerks, led by an Embry-Riddle graduate, offered to provide an empty airframe shell at a large discount for an aircraft known as the Vampire 9. Vampire 9 was appealing as it was an exciting design that met or exceeded most of the team's requirements:

- Durable carbon-fiber composite construction
- Large payload capacity and area
- Stable and efficient aerial platform
- Simple design

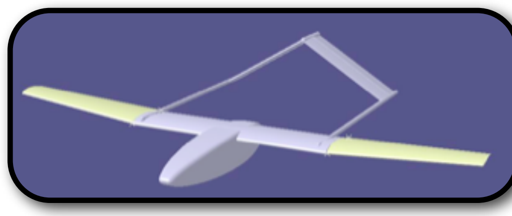


Figure 4.3.2: Vampire 9

Almost the entire airframe is fabricated from carbon-fiber composites. The fuselage is made of a carbon-fiber/NOMEX™/carbon-fiber sandwich. The NOMEX™ is used to add strength in the direction orthogonal to the carbon-fiber weave. The wing and tail sections are made of an expanded polystyrene (EPS) core wrapped in a layer of carbon-fiber. The tail booms are made of unidirectional mandrel-wound carbon-fiber tubing. The aircraft's composite construction has three major benefits:

- A high strength-to-weight ratio.
- Increased durability. When compared to other materials such as balsa wood and fiberglass, carbon-fiber has a greater resistance to fatigue, it is non-flammable, and it is corrosion resistant.
- Ease of repair. The airframe can be repaired by simply applying a carbon-fiber patch with epoxy which will actually make the airframe stronger at the cost of a small gain in overall weight.

The design of the airframe allows for a large payload area of over 2300 cubic inches weighing only 17 pounds. This allows for a remarkable payload capacity of 15 pounds.

In flight, the airframe is a stable and efficient platform. The wings have a six degree dihedral, which helps Vampire to maintain performance even in strong winds. To test this, the aircraft was flown in 25kt winds with the autopilot set to heading hold mode. The autopilot was capable of holding a heading within two degrees. Vampire is energy efficient as it has a drag coefficient of just 0.19 and uses only 0.052 kW per pound during cruising conditions. Reasons for this high efficiency are that the wings do not include control surfaces, which would have increased drag during turns, and the motor is located behind the majority of the aircraft, which decreases the aircraft surface area affected by the prop wash.

The airframe is designed to be simple and rugged. It uses only two control surfaces, which are two ruddervators on the tail. The airframe easily breaks down into the fuselage, three wing sections and two tail sections for ease of transportation, which satisfies our simplicity and modularity goal. It has also been designed with the ability to take off from a launcher and perform a deep-stall belly landing, allowing the aircraft to be flown from an unimproved location increasing options for flying sites.

4.3.3 The evolution of Vampire 9S

Vampire 9 initially failed to meet AEC2, AEC5, and AEC7 as it was designed with long range missions in mind and had a high-efficiency airfoil and a gas engine. Also, the aircraft's 9 foot wing was a single piece, which would have made it difficult to transport. Hearing this, DynaWerks generously offered to help the team customize the airframe to meet the remaining requirements. DynaWerks provided a high-lift wing, and the team added the additional requirements that the wing be capable of breaking into three pieces for transport, that the servos for flight surface control be moved from the tail to the wings for easy access, and the fuselage access hatch be made from fiberglass to allow for radio frequency permeability. The team decided to split the wings just outboard of the tail boom pylons, allowing the aircraft to be broken down into "transport mode" (see Figure 4.3.4). Transport mode allows all the critical avionics to remain on the central fuselage section, minimizing the number of interconnects that need to be disconnected and reconnected, improving compliance with *Quality Goal 4: Maintainability*.

Figure 4.3.3: Vampire 9S in Flight

Figure 4.3.4: Transport Mode

4.3.4 Moving from Gas to Electric

Based on the aircraft evaluation criteria, the aircraft needed to be capable of flying for 45 minutes at a speed of 44.4 mph with a load of at least 7 lb. The team selected the Hacker A60-18M outrunner brushless motor in combination with a Castle Creations 110HV electronic speed controller (ESC), a pair of Thunder Power eXtreme 6 cell series lithium polymer batteries, and a 20x12

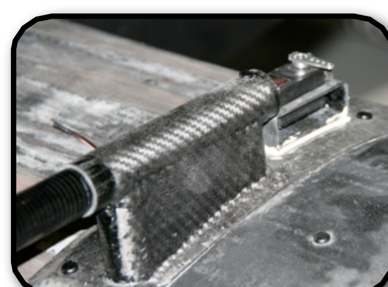


Figure 4.3.5: Wing-mounted servo

carbon-fiber laminate folding propeller. This combination of batteries, ESC, and propeller allows the motor to spin the prop at a maximum rate of 8600 RPM, which provides more than sufficient thrust for Vampire. Vampire is capable of a maximum flight time of 1 hour with a full competition load-out.

4.3.5 Tuning the Piccolo for Vampire

Vampire, having only two control surfaces located on the rear of the aircraft, is an abnormal configuration for the Piccolo. The team consulted with Cloud Cap Technology, who were unsure of the ability of the autopilot to fly the aircraft as well as a normal four surface aircraft. The team was unable to use the “ruddervator mixing” that was built-in to the autopilot, as the mixing was incorrect for our configuration. Instead the team set the Piccolo to treat the surfaces as elevons, with one of the elevons being inverted. The tuning process was complicated by the fact that Vampire is inherently roll-yaw coupled, meaning that whenever the autopilot attempts to roll the aircraft, it will also yaw. Sudden large-throw movements of the surfaces can cause the aircraft to oscillate, yawing back and forth. This is not a problem for a human pilot, and in fact makes executing coordinated turns easier, but for the autopilot care had to be taken to make sure that its responses were smooth at all times. The primary method of smoothing out the input was to limit the rate at which the Piccolo was able to move the servos. After changing this setting and slightly tweaking the gains on turn rate, heading, altitude, and airspeed loops, the Piccolo was able to superbly handle the Vampire.

Challenges posed by autonomous takeoff and landing were mostly designed out of the system. The Blackbird UAS’s design makes it easy for the Piccolo Plus to provide autonomous takeoff and landing, despite the fact that there are no additional sensors such as a laser altimeter or ultrasonic sensor installed. Autonomous takeoff is accomplished using a launcher, which is a method well suited to the Piccolo. Autonomous landing, which on the Piccolo consists of flying through a landing pattern before following a shallow glide-slope to a touchdown point, is possible due to the ruggedness of the airframe; the Piccolo can simply fly Vampire gently into the ground without incurring any damage.

4.4 Safety System

The safety system is comprised of three components:

- Reactive Technologies RxMux multiplexer
- Futaba 2.4GHz backup radio receiver/transmitter
- Fail-safe camera and video transmitter

Although the Piccolo autopilot provides a reliable method for switching between autonomous and manual control, the team felt that it was important to implement a backup safety override. The backup override is implemented by three components. The first is a Reactive Technologies RxMux, which is used to switch between servo signals from the Piccolo and a backup controller. The second is the backup controller, which is a Futaba 2.4GHz manual radio control, capable of providing PWM (pulse-width modulation) signals to servos. The third is a backup console, which provides the safety pilot with manual control over the flight surfaces via the backup controller. The pilot has two “pilot consoles” at his disposal: One console is for aircraft control via the Piccolo (Piccolo console) and the other communicates directly to the Futaba 2.4Ghz manual radio control (backup console). At any time the pilot may override the Piccolo with the backup console, whether the Piccolo is in autonomous or manual mode, and take control of the aircraft. In addition, the Futaba 2.4GHz manual radio control has a built-in fail-safe, which, in the event of lost link with the backup console, is pre-programmed to cut the throttle. In the event of lost link with the Futaba 2.4Ghz backup controller one of two scenarios are possible: The backup override is not enabled when lost link occurs and Blackbird will continue to be controlled by the Piccolo, or the backup override is enabled when lost link occurs, in which case the throttle will be cut to zero. In the unlikely case of the former, if the aircraft continues out of range the Piccolo will carry out aerodynamic termination.

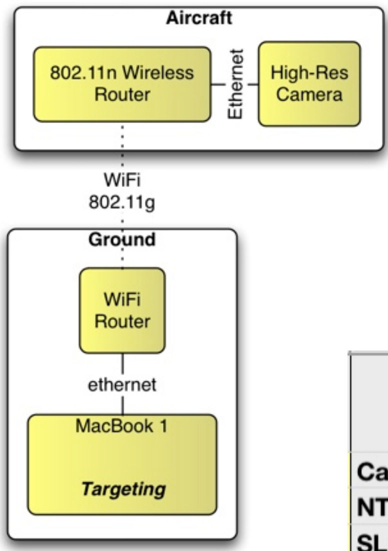
The next component of the safety system is the fail-safe camera and video transmitter. The fail-safe camera is intended to be used primarily for emergency control of the aircraft where the safety pilot is no longer within visual range. In this scenario, the pilot may use either the primary or backup console. This camera is a fixed position forward-looking low resolution analog video camera (described in Table 3.3.1, ST3 and ST9) connected to a BlackWidow AV 2.4GHz analog video transmitter. The BlackWidow AV video transmitter is connected to a 2dBi omnidirectional antenna, is received by a diversity receiver connected to two 14dBi polarized patch antennas, and has been experimentally verified to have a range of about 3 statute miles.

All safety system components run from the main power instead of a backup power supply as the team determined it would be less safe to run from a separate power source. The decision not to use a backup power supply was a difficult one as adding it to better meet *Quality Goal 1: Safety* directly conflicted with *Quality Goal 5: Simplicity.* Despite this, the decision was not made based solely on this conflict. Instead, further discussion revealed that a backup power source, while adding to safety via redundancy, could also detract from it. This is because using a power source separated from the Piccolo would deny the operator the ability to monitor the voltage of the backup power supply, which was deemed unsafe. This, combined with the conflict with *Quality Goal 5* lead to the team's decision to leave out a backup power supply.

4.5 Investigation of High-Resolution Video

The imaging system is a critical component of the UAS, and much research and experimentation was conducted to bring the system to the current design. In deciding which strategies to implement, a spreadsheet, shown in Table 4.2, was developed to compare the different camera and lens options. Initially the team intended to use a fixed position high-res video camera (Table 3.3.1, ST4 and ST9) with a high bandwidth 802.11g wireless connection (Table 3.3.3, ST15). The selected high-res camera had internet protocol transmission capability, meaning it would be able to connect directly to a network and transmit video back to the ground. Full motion high definition video was appealing due to the past experience, where the ability of an operator to clearly see targets from a distance in full motion video would have been appealing. In addition, this strategy would have met the *Simplicity* and *Reliability/Repeatability* quality goals, as the cameras would have connected to the ground using internet protocol (IP) over Ethernet and WiFi (see Figure 4.5.1) with little additional configuration. The team obtained an Arecont Vision AV2100 for testing to investigate this strategy and discovered a problem: The AV2100 used what

Figure 4.5.1:Original Imaging System



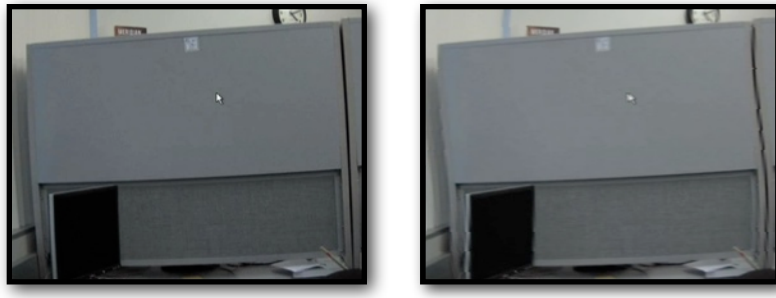


Figure 4.5.2: Rolling Shutter Distortion Effect. Note the waviness of the vertical lines.

Table 4.5.1: Camera and Lens Comparison.

The cells in blue are manipulable by the developer, and the yellow cells are calculated values.

Camera	Altitude (ft)	Airspeed (mph)	Target Area (sqft)	Target Size (ft)	Target Res. (px / target)	In Frame (sec)
Canon DSLR	700	38	2787840	4	326.228136	9.9624596
NTSC	700	38	2787840	4	7.03558593	11.692936
SLR Wide	500	38	2787840	4	38.076496	21.116555
Arecont	700	38	2787840	4	58.5435549	10.244997
Avigilon	700	38	2787840	4	73.5694838	9.5426819

Camera	ResX (pix)	ResY (pix)	Lens DFOV (deg)	Image Size (MB)	View X (ft)	View Y (ft)	Viewing Area
Canon DSLR	3888	2592	78	3.5	890.181	555.241	0.01773
NTSC	640	480	90	NA	1072.02	651.686	0.02506
SLR Wide	3888	2592	179	3.5	3598.21	1176.9	0.1519
Arecont	1600	1200	80	NA	918.999	570.988	0.01882
Avigilon	1920	1080	75	NA	847.933	531.845	0.01618

is known as a “rolling shutter”. As opposed to a global shutter, which samples all the pixels of a photo-sensor at once, a rolling shutter samples them sequentially. When using this sequential method, if the camera moves, the objects in the image will distort in the direction of movement. This can be seen in Figure 4.4.2. Next the Avigilon high-res camera was investigated. The Avigilon used a global shutter, but the video stream from the camera was locked to the vendor’s proprietary software which was designed primarily for security camera use, making it useless for the team’s application.

The next strategy investigated was the use of a high-res still camera (Table 3.3.1, ST5). High-res still cameras have the highest target resolution and use higher quality optics (Table 3.3.1, ST7) when compared with the other imagery strategies. However, using the high-res still camera strategy violated *Quality Goal 5: Simplicity* and *Quality Goal 3: Efficiency* as the only way to interface with such a camera is either via a USB (universal serial bus) connection to a computer or using a servo to manually trigger the shutter, which the team considered to be unacceptable. The team began investigating the strategy further, starting by writing a letter to Canon U.S.A. asking for access to the Canon SDK (software development kit). Canon generously provided the SDK, and with it the team was able to write software that can manipulate every camera setting and take advantage of every feature available on Canon’s entire digital SLR line of cameras. The team then moved to carry out the strategy and the system that was developed is now known as *Target Stalker*.

4.6 Target Stalker

The imaging system, *Target Stalker*, is comprised of five components:

- *Mac Aero*, an Apple Macintosh Mini computer
- Novatel RT2 kinematically corrected DGPS
- Canon 400D Digital SLR still camera
- Point Grey Research Firefly 1394a digital video camera
- Rapid Asynchronous Photo Transfer and Retention System (RAPTOR)

Target Stalker uses three strategies: A fixed position downward looking high-res still camera (Table 3.3.1, ST5), a fixed position downward looking low-res FireWire video camera (Table 3.31, ST3), and an RTK GPS (Table 3.3.1, ST2).

Figure 4.6.3: Canon 400D

Figure 4.6.4: Tamron 17-50 f/2.8

The camera chosen for Target Stalker was the Canon 400D digital single lens reflex (DSLR) camera with a 10.1 megapixel complementary metal-oxide-semiconductor (CMOS) sensor. The 400D was chosen over the other Canon DSLR offerings due to a balance between cost and performance. With its 10.1 megapixel resolution, the 400D is capable of the highest quality imagery, when compared with the alternatives listed in *Table 4.2,* with a pixel resolution of 326.2 pixels per target. The camera can use a wide variety of high quality lenses of varying capability and quality. The team has equipped the 400D with a Tamron 17-50 mm variable focal length lens with a relative aperture of f/2.8 and special hybrid-aspherical lens elements to eliminate ghosting and glare [8]. Changing focal lengths can compress the depth of field of an image; increasing focal length will appear to bring objects closer to the camera and limit the field of view, while shortening it will appear to move them farther away and broaden the field of view. Using a variable focal length lens allows the operators to change the view of the camera depending on the mission.

Using Target Stalker requires two operators: the *Shooter* and the *Analyst*. The Shooter is responsible solely for watching the video display for potential targets and shooting a picture with the 400D if a potential target presents itself. The Analyst is responsible for viewing the images received from the aircraft and analyzing them to identify and log target characteristics. As the Shooter takes pictures of potential targets, each photo is automatically embedded with highly precise data on Blackbird's position provided by a NovAtel 20 Hz update rate, 2 cm positional accuracy DGPS [1].

The RAPTOR (rapid asynchronous photo transfer and retention) system handles the technical aspects of shooting, transferring, and storing photos taken by Blackbird. Even though the data-link only has sufficient bandwidth to transfer the full resolution images at a rate of 0.2 Hz, RAPTOR allows the Shooter to take pictures at a rate of 1.5 Hz in burst fire mode for four consecutive images, or at 1 Hz in continuous mode while the images transfer asynchronously in the background. This is useful, as asynchronous shooting and transfer allows the shooter to capture and embed target images as necessary. Images are transferred using the available bandwidth at all times during flight, not only while the aircraft is over the target area. A lower resolution Firewire video system using a Point Grey Research Firefly operating in real time at a frequency of 60 Hz allows the operator to select prime areas for targeting. This video is encoded on the *Mac Aero* into a QuickTime stream, which is viewable on any computer equipped with the latest QuickTime software.

Once RAPTOR transfers an image to the ground station, the Analyst is responsible for identifying targets within the images, if they exist. If no target can be found in the image, it is moved to a separate folder for archive. If a target is found, the Analyst will identify the characteristics of the target, using photo manipulation tools such as Apple Aperture as necessary.

In addition, if the Analyst recognizes that the images being retrieved are underexposed or blurry, he or she may use the Target Stalker software adjust camera settings for exposure, aperture, shutter speed, light sensitivity, and white balance.

Interfacing with the Canon 400D is the onboard computer, a modified Apple Macintosh Mini dubbed *Mac Aero*. The Mac Mini is a powerful computer in a small form factor, packing an Intel Core2Duo 1.83 GHz processor, 2 GB of RAM, 80GB hard disk dive, DVD burner, Bluetooth 2.0 card, and an 802.11a/b/g/n WiFi card into a 6.5” x 6.5” x 2” aluminum case [9].

Figure 4.6.6: Mac Aero

In constructing the Mac Aero, many of the Mini’s components had to be ruggedized. The stock hard drive, unable to withstand shocks during operation of more than 300g [9], was replaced with an durable 8GB solid state drive, capable of withstanding shocks during operation of up to 1500G [2]. The external AC to DC power supply was replaced with an internal DC to DC regulator, allowing the Mini to run from batteries, and the DVD burner was completely removed to reduce power draw. The stock WiFi patch antenna was replaced with a 1 Watt amplifier and 5.5dBi omnidirectional antenna [3].

4.7 Component Placement

Figure 4.7.1: Component Placement, Top and Side Views

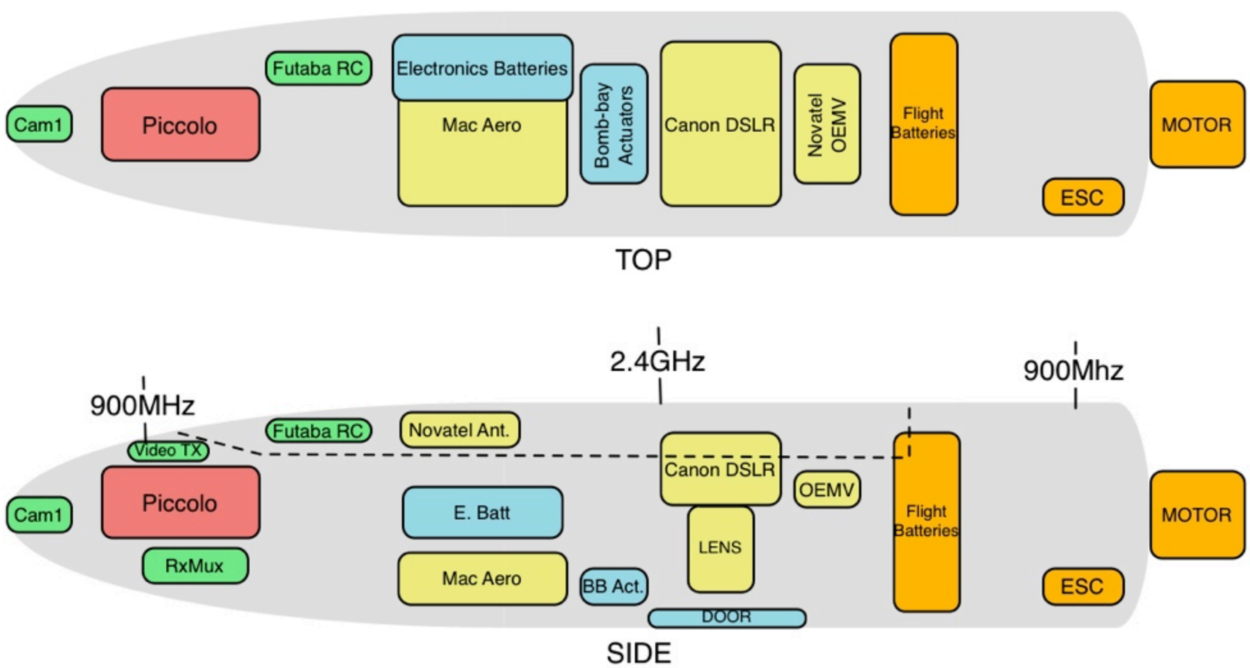
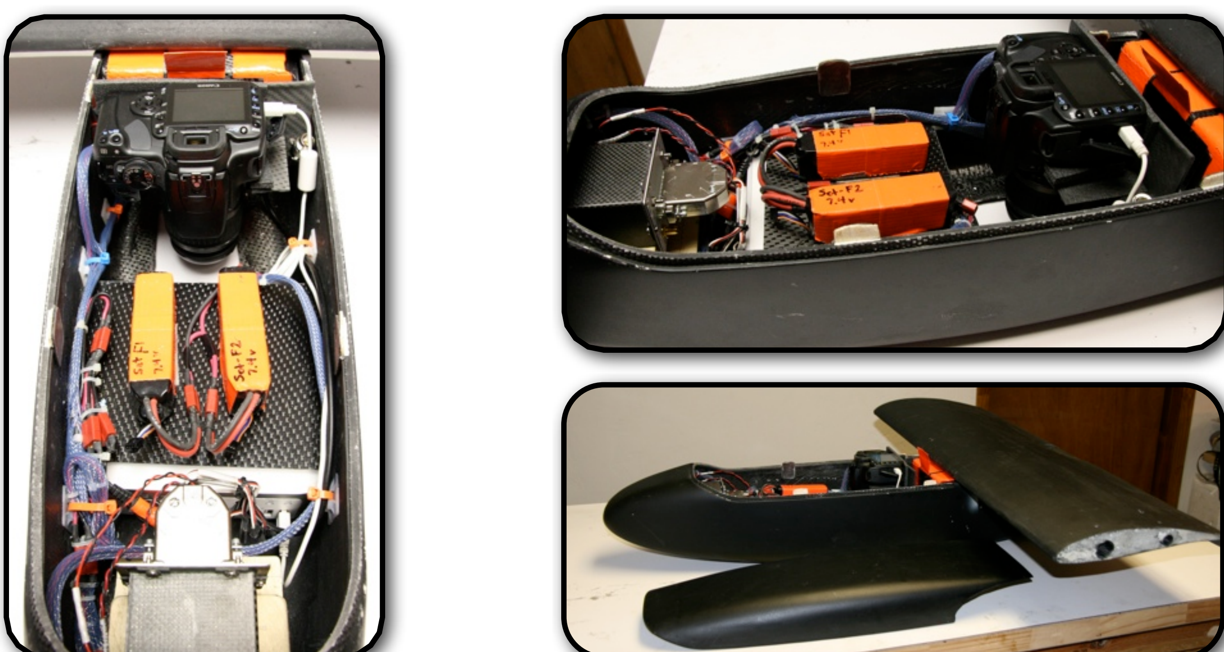


Figure 4.7.1 Caption: The gray area represents the outline of the Vampire 9S fuselage. Component placement is important; incorrect placement of antennas will produce interference, heavy items will change the center of gravity, and the wire runs between components must be considered with respect to length (interference) and simplicity (too many wires).

Figure 4.7.2: Component Placement in Vampire 9S



5 Conclusion

The Blackbird UAS vehicle, *Vampire 9S*, has a stall speed of 27 knots and a maximum measured speed of 73 knots in level flight. It is capable of fully autonomous flight, autonomous takeoff, and autonomous landing via a launcher and a deep stall belly landing. Blackbird's *Target Stalker* provides 10.1 megapixel resolution images of targets with low optical distortion and high color accuracy. Operators using Target Stalker are provided with 326.2 pixels of resolution for a 4'x4' target from an altitude of 700ft AGL and airspeed of 38 kts, which can be used to identify all target attributes. The shutter time and exposure capability of the camera and lens are such that images retain clarity even when the aircraft is flying at an altitude of 50 ft AGL and an airspeed of 60 kts. The Blackbird data-link has sufficient bandwidth to transfer full 10.1 megapixel resolution images at a rate of 0.2 Hz, and *RAPTOR* allows the operators to take pictures at a rate of 1.5 Hz in burst fire mode for four consecutive images, or at 1 Hz in continuous mode while the images transfer asynchronously to the ground station. Target Stalker and RAPTOR are made possible by the *Mac Aero*, a ruggedized Apple Macintosh Mini.

The Blackbird UAS was designed with safety, reliability, performance, maintainability, and simplicity as its primary goals, and the team believes that the system will be capable of attaining the majority of key performance parameters available in the 2008 AUVSI UAS competition.

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